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THE MOVEMENT, STRUCTURE AND BREAKDOWN OF TRAILING VORT?CES FROM A ROTOR BLADE

by

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SUMMARY

The results of some flow visualisation experiments on the trailing vortices from a model rotor blade are presented. It is found that, at low tip-speed ratios, trailing vortices close to the leading edge of the disc first pass up through the disc before entering the main flow field. At the rear of the disc the vortices maintain a regular pattern relative to each other. The vortices are fully rolled up in about 60° of azimuth movement of the blade.

Measurements with a hot-wire anemometer show that the vortex core is about one-tenth of a blade chord in diameter, which is consistent with a laminar core state. Outside the core the velocity field is irrotational.

Some observations have been made of a trailing vortex as it approaches the support pylon. The vortex at first follows the pylon contours and remains a tightly-rolled core, but it ultimately leaves the pylon surface and its structure breaks down, rather like the vortices from the leading edges of a delta wing.

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INTRODUCTION

The advances[1,2] which have taken place in the calculation of rotor blade loadings now indicate that our greatest lack of knowledge is of the geometry and dynamics of the near wake. We have clear evidence[3] that the tip vortices do not follow the skewed helix which the tips themselves trace out in space. In fact the distortion may be such that tip vortices and blades come close together, if not into actual contact, at certain azimuth positions. When this occurs, very marked changes take place in the true loading[1], and big differences between the results of experiment and of a theory which omits wake distortion are to be expected.

A further problem in the calculation of blade airloads is that the mathematical models used are themselves open to criticism because they

assume that the trailing vortex sheet rapidly rolls up into vortex filaments. At any appreciable distance (greater than a chords length, say) from a vortex this cannot be a significant objection, but for smaller distances it is obviously necessary to have a better idea of the induced flow field. Thus Simons[4] has shown that there can be large reductions in the predicted peak loadings on a blade if a Rankine, rather than a point, vortex is assumed. It also seems likely that the wake distortion itself will depend upon the vortex velocity field, particularly as much of the distortion originates at the points where vortex filaments pass over each other.

Our principal aim, therefore, was to obtain more data on the structure of the trailing vortex from a rotor blade. Unfortunately this is not very easy to do since carrying a probe around with the blade is likely to interfere with the flow and, on the evidence[5,6] available, the vortex is not fully rolled-up until at least one-half a blade radius from the tip. At that distance, of course, the wake distortion will certainly move the vortex and the problem then is to find it. Thus our first task was to locate the trailing vortices in space, in the hope that we might then be able to study their structure in some way, and our first experiments were exercises in vortex flow visualisation.

This, of course, has been done before by several people, but most extensively by M. Tararine[3]. Tararine in fact demonstrated the distortion caused, at the sides and the rear of the disc, by the mutual interference of successive trailing vortices. Sufficiently far downstream the trailing

vortices have all moved so that they lie, almost as a vortex sheet, in a curved surface. Along the edges of the disc there is, at moderately low tip-speed ratios, a large upwash which keeps the trailing vortices almost in the plane of the disc. Numerical calculations of this type of distortion have been described by White[7] and Scully[8]. But elementary considerations suggest that there ought also to be, at low tip-speed ratios at any rate, substantial wake distortion close to the leading edge of the disc. Any trailing vortex from a blade creates an upwash outside itself; therefore, as the vortices move aft relative to the disc, those at the front create an upwash field which extends for some way over the disc until the vortex filaments are too far below to have significant influence.

This sort of distortion was envisaged by Miller[9] and has been demonstrated numerically by Scully[8]. Ham[10] made some measurements of the instantaneous pressures on a blade in the $= 180^{\circ}$ position, and found very sharp pressure peaks which would be consistent with the presence of a vortex close to the blade. But the only direct evidence of its existence has been given by Gray[11], who measured the vortex positions of a rotor in ground effect by trailing smoke from a blade tip. Gray shows the paths of a tip vortex for various values of tip-speed ratio and these clearly indicate that the vortex remains above the plane of the disc for a short distance before descending into the general downwash field. However, he gives no photographs for he was not directly interested in this phenomenon and he does in fact report that the flow is very unsteady in certain circumstances. Therefore, since this is a low tip-speed ratio phenomenon and our large wind

tunnel limits rotor experiments to these flight regimes, it was felt that to try to reveal this particular wake deformation would give an extra purpose to the flow visualisation programme.

The material presented in this paper falls into three parts. The first, which is summarised in a film, is concerned with the flow near the leading and trailing edges of a rotor disc. The second follows naturally, since the results for the flow at the rear of the disc made it comparatively easy to get some idea of trailing vortex structure simply by placing a hot-wire at the appropriate position in the flow. The third part, which deals with some aspects of vortex flow in the vicinity of a body, was not originally planned, but came as a pleasant surprise, particularly in view of the other interests of the University in vortex flows.

APPARATUS AND PROCEDURE

The experiments were carried out on a 9' diameter, two-hinged-blade model rotor of 4 inches chord in the 15' x 12' working section of the low-speed wind tunnel in the University of Southampton. A general view of the rig is shown in Fig. 1. The maximum tunnel speed in this section is such that with a reasonable rotational speed, tip-speed ratios greater than 0.25 cannot be achieved, but this was not too restrictive. The smoke generator was of a normal commercial type in which oil is allowed to come into contact with a heated plate and the resulting smoke is forced through a nozzle under pressure from a carbon dioxide storage bottle.

To reveal the effect of blade position or flow structure and vortex growth the following procedure was used. The region of flow under

examination was illuminated by a flash triggered by the shutter of a movie camera, and the rotor was arranged to turn at a speed such that the blade passage frequency was very slightly higher than the camera shutter speed. Thus the impression received by the film was of one blade advancing very slowly around the disc. For this technique to be convincing the blades must be properly in track, otherwise the image is apparently that of a single blade which is oscillating as it rotates. As always in flow visualisation the principle problem was to get sufficient light into the right place and then to find a convenient spot for the camera. Broadly speaking the illumination of the smoke has to be perpendicular to the viewing plane. Thus in the film sequences and still shots to be described the smoke, camera and light-source were all placed with the primary aim of getting good pictures.

The hot-wire anemometer which was used to study the vortex velocity field was kindly loaned to us by Dr. P.O.A.L. Davies. It is of the standard constant current variety with a wire about $\frac{1}{8}$ inch long and 5 microns in diameter supported between 30 s.w.g. prongs. A feature of the equipment is that the wire output is linearised before presentation so that a direct reading of velocity is possible.

RESULTS

Rotor Flow Visualisation

The results obtained are presented as a movie at the end of the lecture, but is worthwhile to consider a few features which are best brought out by stills.

Fig. 2 shows a sequence for a case where the tip-speed ratio is 0.04, the collective pitch is 8° and the shaft axis is tilted forward at an angle of 8°. Smoke is injected in a narrow vertical region at an azimuth angle of 180°. In the first frame of Fig. 2 the blade is about 45° from the smoke, but has not yet passed through it. In the final frame the blade is about 30° of azimuth beyond the smoke. Thus the first visible vortex in the first frame is trailing from the blade which passed through the smoke somewhat less than one-half a revolution earlier. The second clear vortex, i.e. closest to the pylon, is the trailing vortex from the blade which is again approaching the smoke.

Several points are worthy of note. First of all there is a very strong upwash ahead of the disc in this flight condition. Secondly while two of the vortices have a very clear cut "eye", the smoke in the remaining (earlier) turns is diffused. Finally, when the blade is in the vicinity of the plane of the smoke, the trailing vortex from the preceding blade is above the plane of the disc, whilst the trailing vortex from the blade in the picture is below the disc. In these pictures the camera is slightly below the disc plane at $\psi = 180^{\circ}$. However, still pictures taken in the plane, definitely show the vortex to be above the blade. Thus the trajectory of the cross-section of a vortex at $\psi = 180^{\circ}$ is an arc at first directed upwards and then downwards, much in the same manner as calculated by Ham[10]. The vortex is above the disc plane for a time which is about that required for one-half a revolution of the rotor. This is in agreement with Gray's results[11]. Another point of agreement with Gray is shown in the difficulty

which is experienced in obtaining a clear "eye" for more than a very few turns of the wake. This phenomenon is discussed in greater detail below (Sec. 4). The sequence of frames when the blade has passed through the smoke allows us to form some idea of the time required for a trailing vortex sheet to fully roll up. It is clear from the last frame that rolling-up is not quite complete but the process does seem to have stopped in the first frame when the blade has turned about another quarter of a revolution. We may conclude, therefore, that the rolling-up process is complete in about the time taken to travel one blade radius. In terms of the blade chord, this is in general agreement with the distances which have been found for the completion of the rolling-up process behind straight wings[5,6].

The same kind of arguments which predict the distortion at the front of the disc indicate that at the rear the vortices should maintain their distances and distribution. This is confirmed in Fig. 3 which shows the cross-sections through the trailing vortex system in the vertical plane $\psi = 0^{\circ}$. As would be expected, these cross-sections are spaced farther apart than the corresponding cross-sections at the leading edge of the disc and, generally speaking, the central "eye" is more persistent. The arrangement of vortices at the trailing edge of the disc is so regular that the results for only one case are indicated in the film. A diagram of the relative vortex core positions at the front and rear of the disc, for a range of tip-speed ratios, is given in Fig. 4. It is clear, from a comparison of the positions of corresponding cross-sections, that considerable vertical distortion is taking place, but the investigations do not show whether a vortex may actually come into contact with a blade. From the photographs it seems obvious that

this must happen but it is, of course, possible for the vortices to distort laterally, so that they cross the disc plane outside the disc. Some indication that this may occur has been given by Scully[8]. Also the exact time spent above the disc is a crucial factor, but the results certainly suggest that blades and vortices must pass very close.

In a flight condition corresponding closely to that of Figs. 2 and 3, Gray[11] observed a large vertical oscillation of the vortex at the leading of the disc. No such oscillation was present in our tests. To convey some idea of the general steadiness of the flow it should perhaps be stressed that these pictures are not the outcome of high-speed photography, but are essentially a succession of stills taken very slightly more than one-half a revolution apart.

The Velocity Field of a Vortex

The very regular nature of the flow at the trailing edge of the disc offers a convenient method of measuring the structure of, and distribution of velocity around, a vortex. If a hot-wire anemometer can be placed along the line of travel of the eyes of the vortices, then a characteristic signature will be produced each time a vortex passes over the wire. Provided that the mean convection speed is small compared with induced velocity, the anemometer output should be a very good indication of the distribution of velocity within a vortex. Also, by placing the hot-wire at different points on the wake spirals, it is possible to get some idea of the development and growth of a vortex with time.

The hot wire was placed, in the plane $\psi = 0^{\circ}$, with its length

parallel to the vortex axis, so that it was most sensitive to velocities in the plane of the induced velocity field. Coarse adjustments to the position were made by eye, using smoke as a guide to the line of convection. Very fine adjustments to the position of the wire relative to the vortices were made by making very small changes to the tunnel speed.

Typical records of the anemometer output are shown in Figs. 5, 6. These are for a vortex which is somewhat less than one revolution old. Because a hot-wire is a rectifier its output is always positive whatever the magnitude and direction of the velocity. Thus if the centre of a vortex passes over the wire, the indicated velocity rises, from the mean value, to a maximum and then falls very rapidly back to the mean value, only to rise again to the peak followed by a reduction back to the mean value. The occurrence of a steep-sided trough in the record is a good indication that the centre of the vortex is actually passing over the wire.

The records show that for a mean convection speed of about 12 ft./sec. the peak velocity is about 45 ft./sec. They also show the existence of a core of finite dimensions. The precise dimensions of this core were not easily determined, partly because of its small size, and partly because the flow within the core appears to be unsteady. In addition there were some very small, comparatively long period, fluctuations in the paths of the vortices, so that only a small fraction of the total number of traces could be used for analysis. (This particular unsteadiness is attributed to the influence of the wake of the pylon). Nevertheless it was possible to obtain sufficient data to get an approximate idea of the vortex size and the results

are summed up in Fig. 7. For the limited number of tests done no effect of wake age or blade Reynolds number was detectable within the overall scatter. The average vortex core diameter is slightly less than 10% of the blade chord and a comparison between the rate of growth with time and Lamb's[12] theoretical solution for the decay of a viscous point vortex suggests that the core is laminar. There is thus some conflict of experimental evidence, for the hot-wire anemometer records clearly show the existence of high frequency fluctuations within the core. But some guide to what is really happening may be contained in the traces themselves.

In Fig. 6 the vortices are moving from left to right relative to the wire, and it will be observed that generally the leading edge of the core trace is much smoother than the trailing edge. This suggest that the recorded turbulence may be due to the interference of the probe itself with the flow within the core.

These results have implications for both theory and for model testing. For if the cores of full-size vortices are really of the same proportions, then, in calculation, it should be sufficient to represent them by point vortices. But if the cores of full-size trailing vortices are really turbulent, rather than laminar, then the effective kinematic viscosity within them could easily be fifty times greater, and the core diameter would then be of the order of a blade chord. There is some evidence from Spreiter and Sacks[6] that vortices may indeed be of these dimensions. We must also conclude that higher harmonic loadings measured in model tests may not be fully representative of full-scale, unless steps are taken to ensure that the

vortex cores are turbulent and remain so.

Outside the core our measurements indicate that the flow is virtually irrotational. Superimposed upon the record in Fig. 5 is a curve representing the induced velocity field due to a pair of point vortices situated at the core centres, and chosen in strength so as to give the correct induced velocity at a small distance from the centre. The fit is very good. Thus the classical Rankine vortex, consisting of a "solid" core embedded in an irrotational flow, is a suitable model for blade tip vortices.

THE BREAKDOWN OF TRAILING VORTICES

The above account represents the limit of what it was possible to plan on the basis of some preliminary flow visualisation experiments. The results have an intrinsic interest for they do give confidence in certain applications of theory but, as always, they pose more questions than they answer. It is hoped to be able to provide more answers at another time and suitable experiments are now being planned.

In the course of our investigations another phenomenon was revealed, and we would like to devote some time to this because it may be important to V/STOL design, and because it has a wider application in fluid mechanics.

The vortices in Figs. 8, 9, 10 were revealed by emitting smoke from a fixed nozzle, with the rotor and the tunnel fan turning at low speed. Under these conditions some of the smoke is trapped in the boundary layer of the blade and is carried round with it. As the blade moves away from the injection point the trapped smoke passes into the trailing vortex. Since its velocity is very small most of the smoke enters the core and very clear

flow patterns are obtained until the supply of smoke is exhausted. A disadvantage of this technique is that the smoke trail is non-uniform. Close to the injection point there is an excess of smoke and the picture is consequently diffuse. This excess does, however, disperse rapidly. Typical examples are given in Fig. 8 which shows trailing vortices leaving the blade tips and advancing towards the pylon.

The subsequent behaviour is best revealed by a camera mounted on the foot of the pylon. As the vortex approaches the pylon it deforms, since that part closest to the leading edge is slowed down. The limit of this deformation is shown in the third plate of Fig. 9 when the vortex appears to be wrapped around the nose of the pylon. There is in fact some accompanying distortion in a vertical direction so that the vortex core also runs down the nose of the pylon. A little while later the clear cut core has begun to break up, as plate (iv) shows, from both ends. The flow in the pylon boundary layer becomes more diffuse, but the core itself begins to spiral in a helix, whose pitch is of the order of a core diameter, plate (vi). As the vortex moves across the pylon this spiralling, or "unwinding", of the vortex propagates outwards towards a similar spiral which is moving inwards from the edge of the vortex. Thus, within a very short distance, the vortex structure has changed from a tightly-rolled core to a diffuse, swirling flow. Some further idea of the changes which have been brought about is given by Figs. 10, 11. Fig. 10 shows a cross-section of the moving vortex- obtained by illuminating a darkened tunnel with only a slit of light - as it passes the pylon. The white line is simply a marker showing the pylon leading edge.

The first cross-section is almost circular, and a definite, but more diffuse, core can still be observed in the third cross-section, but the next picture shows the structure to have become without form. Fig. 11 shows how the velocity, measured with a hot-wire anemometer, varies in a vortex core just ahead of the pylon and within a vortex which has broken down. Although the second trace shows the existence of a periodic disturbance, no clear structure is evident.

This phenomenon is reminiscent of the breakdown which occurs in the leading edge vortices formed above narrow delta wings. Fig. 12, which is due to Krishnamoorthy[13], shows how this breakdown develops, on a very slowly oscillating wing from a spiral whose pitch is of the order of a core diameter, into a diffuse turbulent "bubble". The exact mechanism of the breakdown has not yet been properly established although a number of theories have been suggested. But it is known that when a vortex breaks down there is a sharp rise in the intensity of the pressure fluctuations on the surface beneath the breakdown. Thus if, as seems likely from these tests, breakdown occurs when a trailing vortex passes over a fuselage, there could be high noise and vibration levels within the fuselage. Another point of interest to helicopter designers is that a vortex which has broken down in this way will not have a very peaky induced velocity field. Therefore, it might be expected that the interference with following blades, e.g. in a tandem rotor, will be much reduced.

A further possibility is that trailing vortices can break down without necessarily coming into contact with a solid body. This is certainly

true of leading edge vortices, although the presence of an obstacle does tend to precipitate breakdown[14]. In this connection it is interesting to note that Gray[11] also observed a sudden change in core structure, with the disturbance propagating away from the leading edge of the disc in both directions along the vortex filament. Gray explains that this is the reason why a clear-cut structure is not visible beyond the third turn.

Therefore, since we have observed the same difficulty at the leading edge of the disc, it is likely that vortex breakdown occurs somewhere along the vortex. But it is not easy to argue that this breakdown is spontaneous, since the clear-cut structure does persist at the rear of the disc. It is necessary, therefore, to postulate some interference with a vortex which has broken down, and this could very well be due, at the front but not at the rear, to a blade passing through, or very close to, a vortex. Some support for this is contained in Fig. 9, for there is evidence to suggest that the breakdown propagating inwards towards the pylon originated at about 270° azimuth. In this region the wake distortion sweeps the vortices up and flow visualisation shows that they lie very close to the blade tips.

CONCLUSIONS. FURTHER DEVELOPMENTS

Visualisation of the flow through a model rotor by means of smoke has shown that, at low tip-speed ratios, the trailing vortices at the leading edge of the disc first pass up through the rotor, and then move down with the general downwash field. At the rear of the disc, the vortices move faster than the mean downwash but maintain their relative positions approximately on a straight line. There is, therefore, considerable vertical distortion of the first few turns of the helical wake in a fore-and-aft plane. The

trailing vortices can be regarded as fully rolled-up by the time the blade tip has travelled about one blade radius.

It is our intention to extend this work to rotors with more blades and to examine different azimuth stations. It is also hoped that the technique can be developed to deal with tandem rotors.

Measurements, on a model scale, with a hot-wire anemometer have shown that the vortex core is less than about one tenth of a blade chord in diameter, and that the flow field outside the core is essentially irrotational. If this result carries over to full-scale, then the concept of vortex filaments should be quite adequate for use in mathematical models for blade loading calculations. This conclusion will, however, have to be checked further, since the vortex core size indicates that the flow within it is laminar. The next hot-wire anemometer measurements will, therefore, be made with the blade tip regions roughened to try to establish turbulent flow. It is thought that this may lead to substantial increases in the core size.

Finally, it has been shown that a trailing vortex undergoes a complete change in structure after only part of it has been in contact with a solid body. The reason for this is not known, although there are strong similarities with the vortex breakdown phenomenon.

In general we conclude that much more needs to be done to establish the validity, or range of application to full-scale, of model rotor tests. This is particularly true of the boundary layer state and, although it is not immediately obvious from the presentation, there have been indications of appreciable tunnel wall effects. But tests on a rotor may have something

to offer to the general field of fluid dynamics research. Hot-wire measurements made at various points in the trailing vortex of a blade provide a convenient way, than measurements behind a fixed wing, of examining the development of a vortex with time. It may also be possible to carry out more easily controlled investigations into vortex breakdown.

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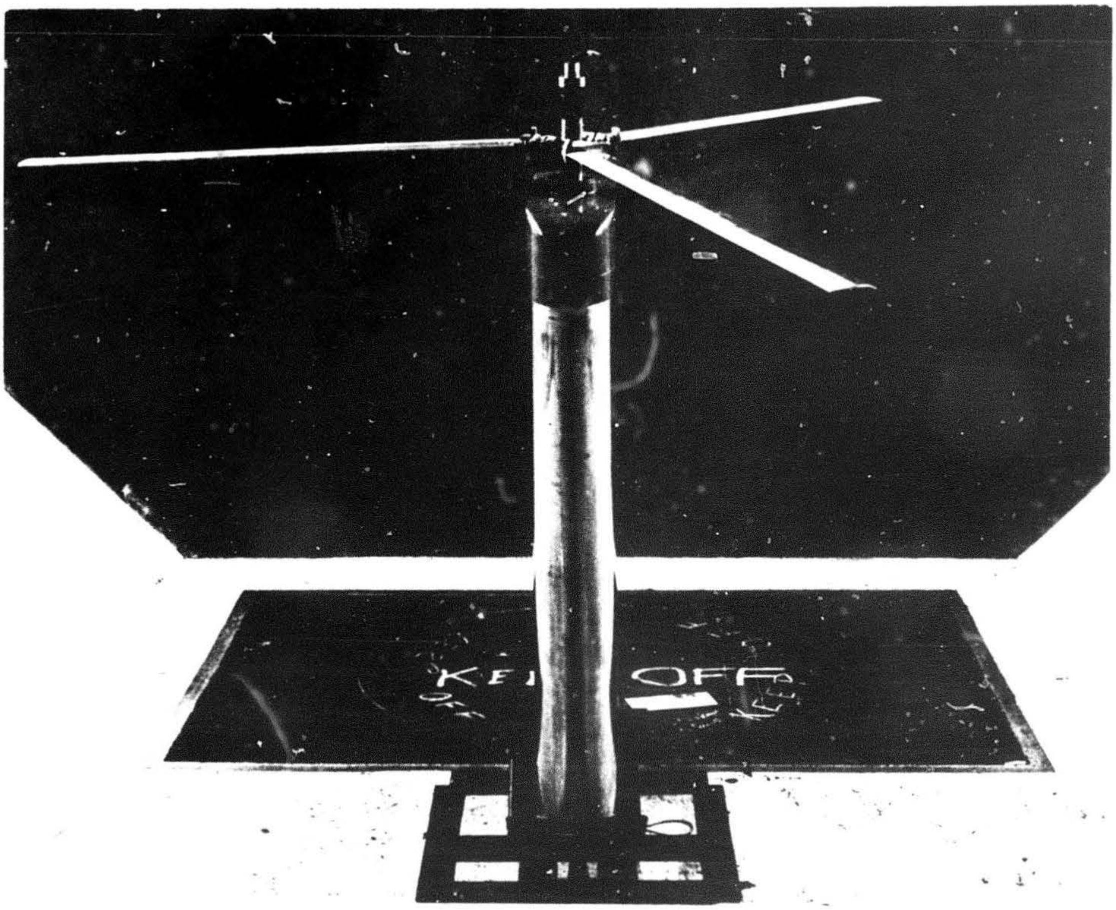

FIG. 1. General view of rig.

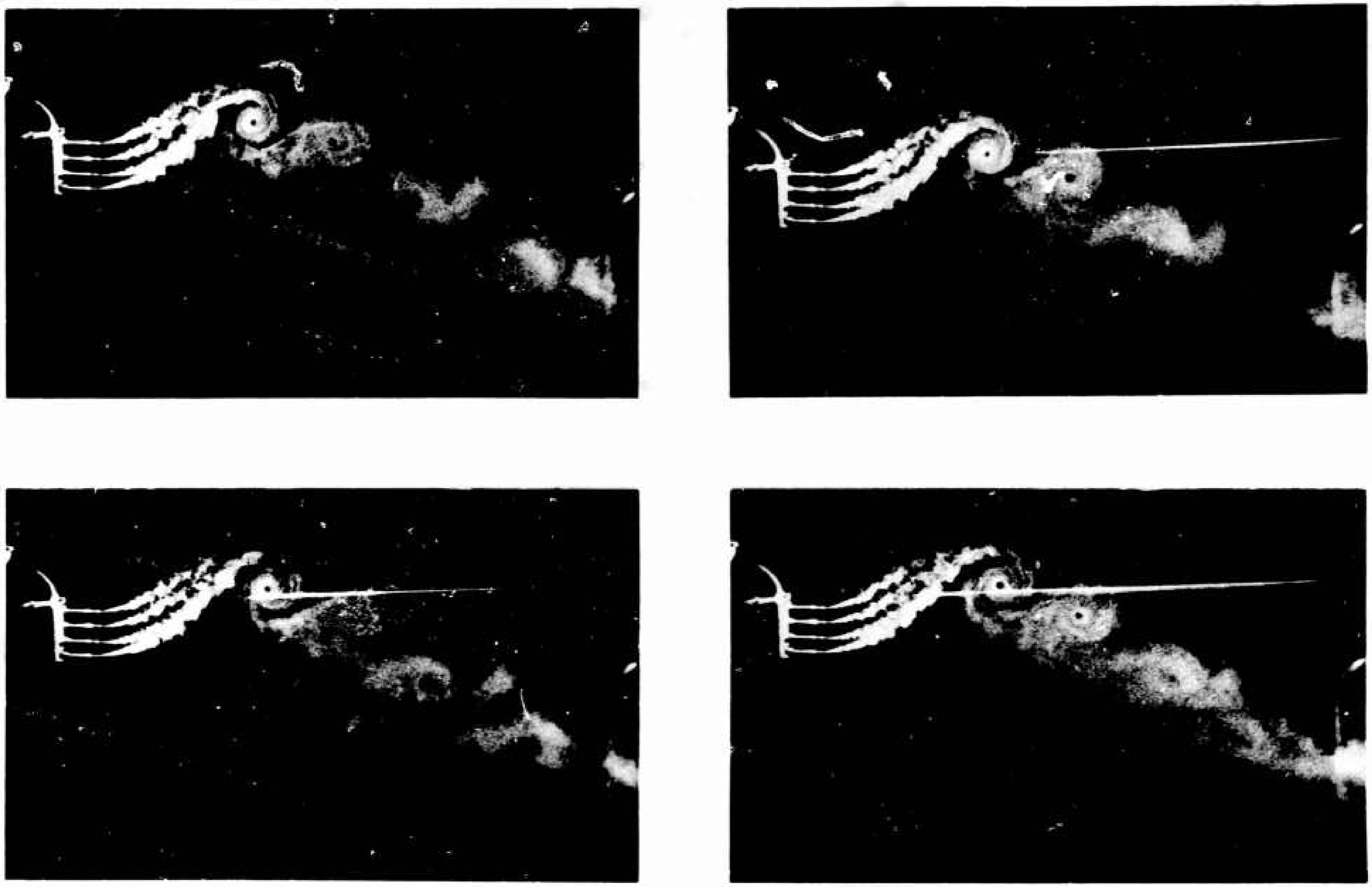

FIG. 2. Movement & Growth of Vortices at leading edge of disc. Rotor speed 240 r.p.m. Collective pitch 8°. Shaft inclination 8°. Tip-speed ratio 0.04.

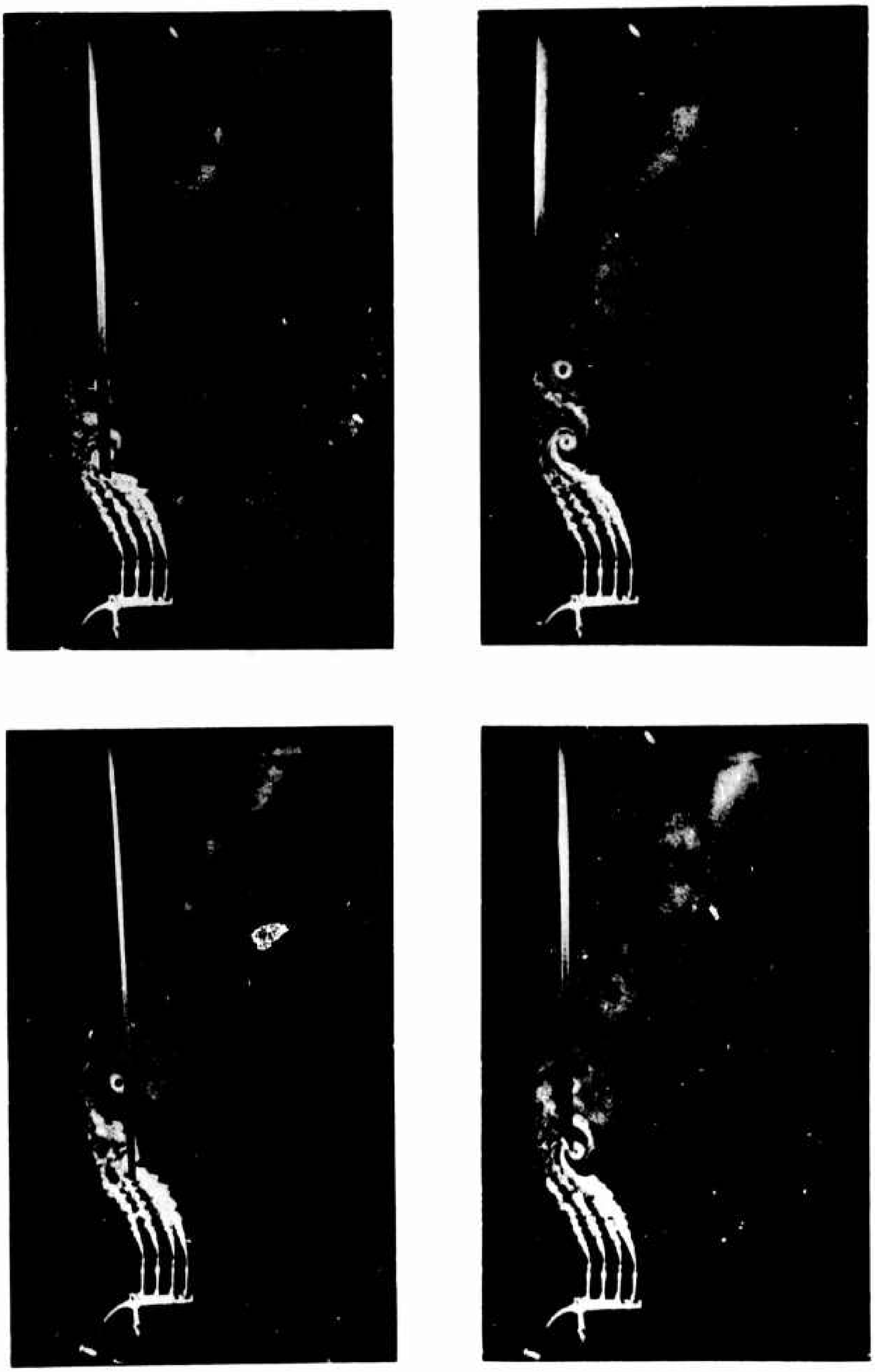

FIG. 2 contd. Movement & Growth of Vortices at leading edge of disc.

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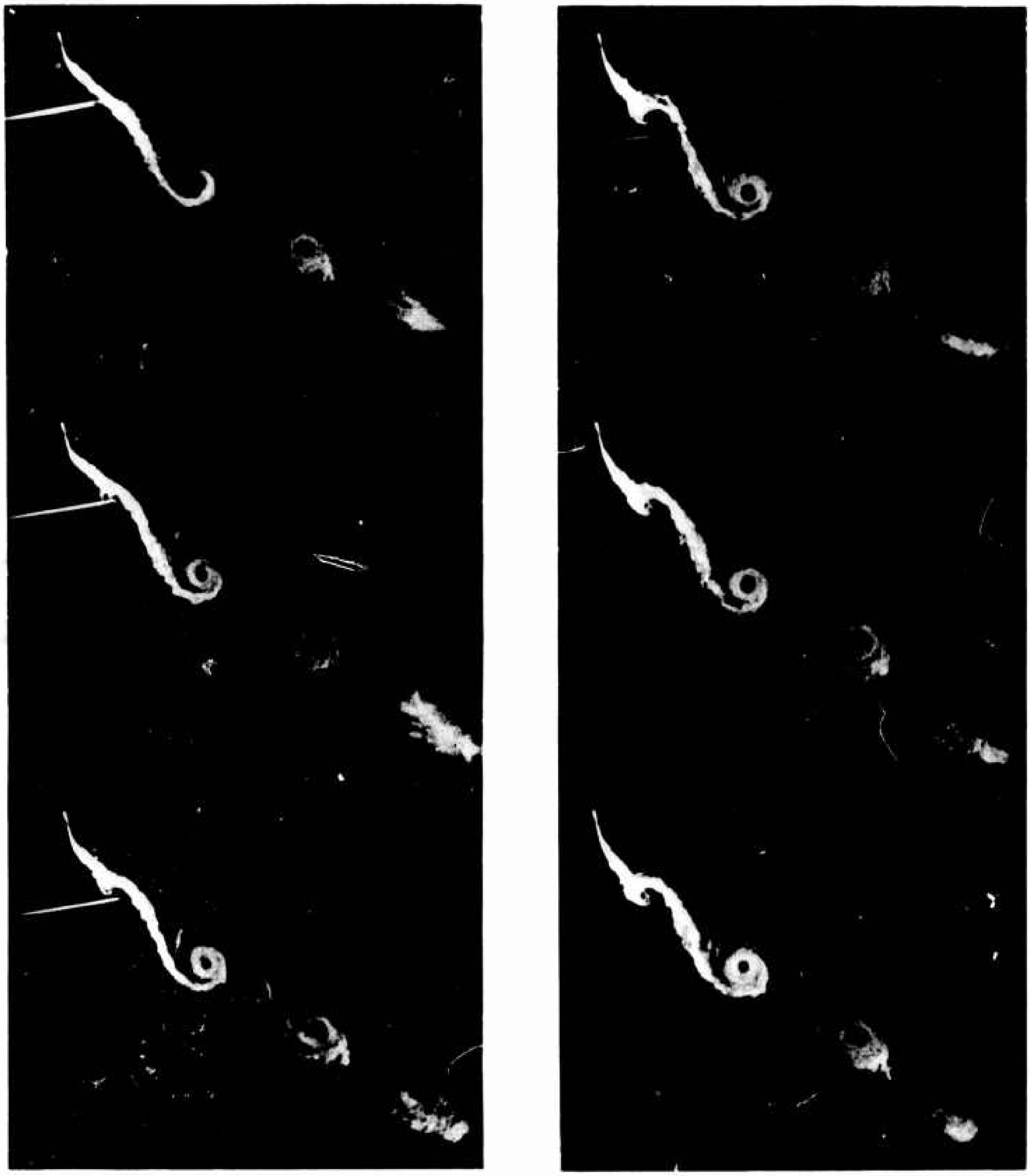

FIG. 3. Movement & Growth of Vortices at rear of disc. Rotor r.p.m. 240. Collective pitch 8°. Shaft inclination 8°. Tip-speed ratio 0.04

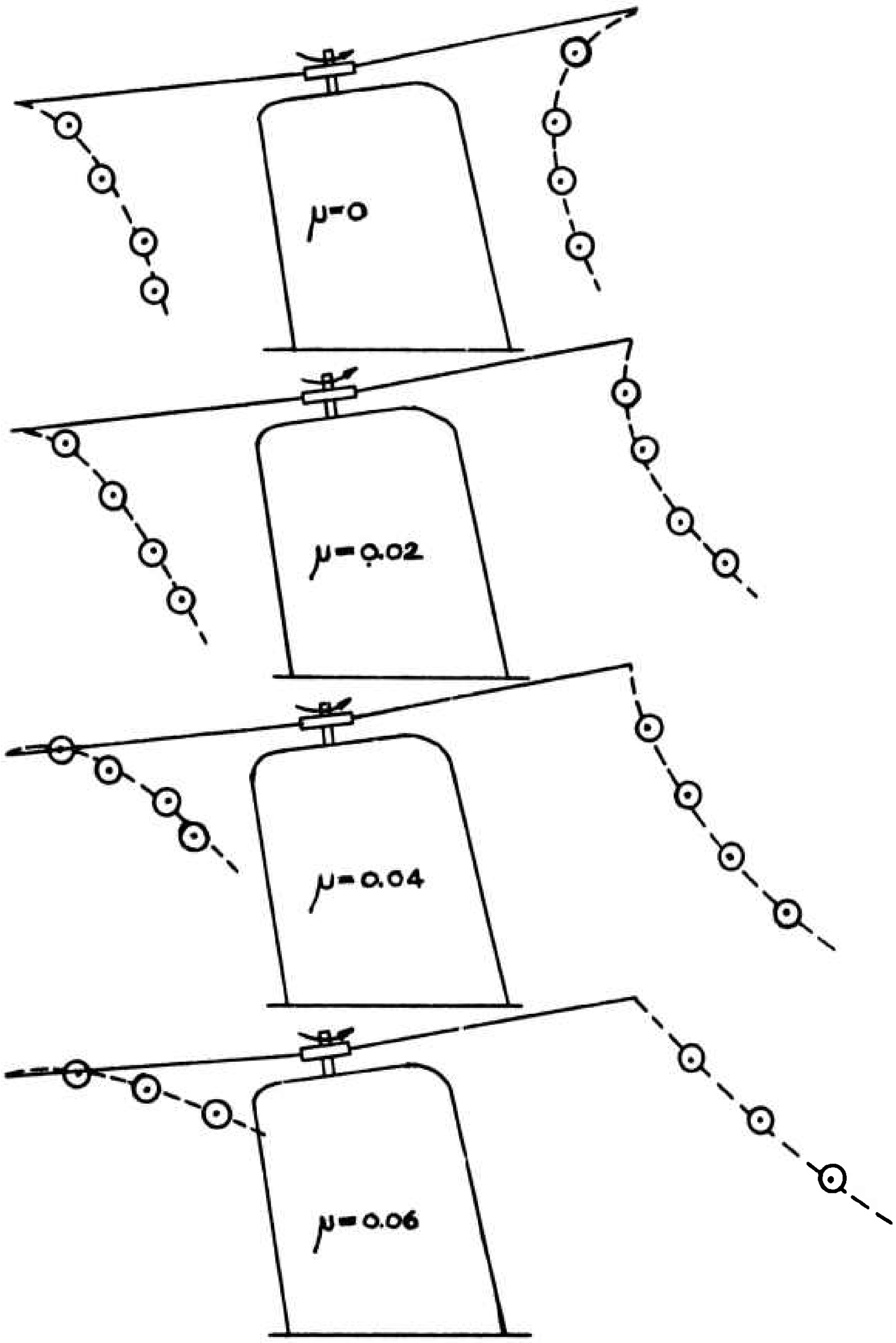

FIG. 4. Vortex paths in the fore-and-aft plane. Rotor speed 240 r.p.m. Collective pitch 8°. Shaft inclination 8°. Note: Ground plane is 6 ft. below rotor hub, and is not shown on the diagram.

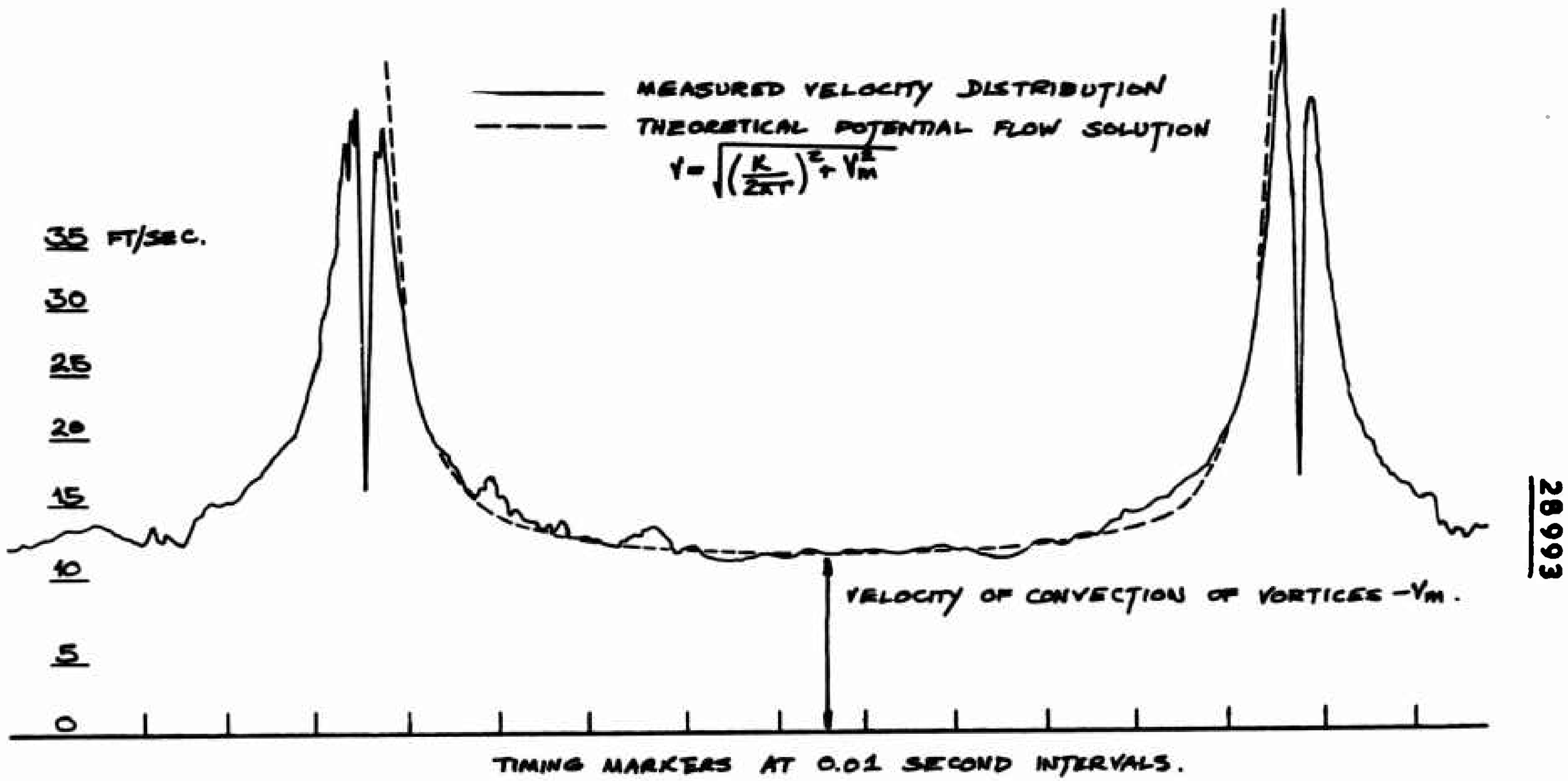

FIG. 5. Hot-wire anemometer record. Wake age ± 300° of azimuth. Rotor speed 300 r.p.m. Collective pitch 8°. Shaft inclination 8°. Tip-speed ratio 0.04.
Note: The vortices are moving from left to right relative to the hot-wire probe.

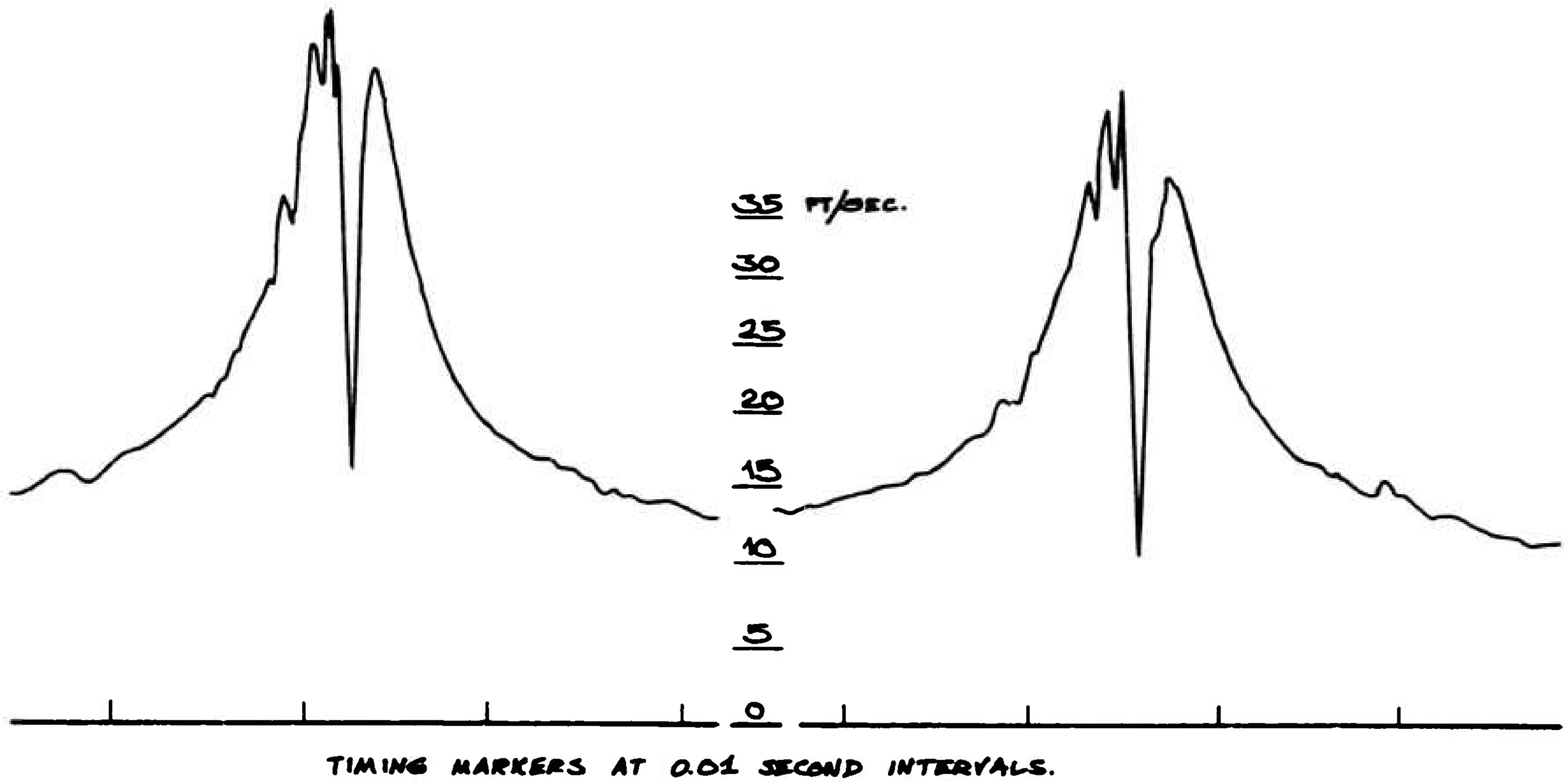

FIG. 6. Sample records from hot-wire anemometer. Wake age ± 300° of azimuth. Rotor conditions as for Fig. 5.

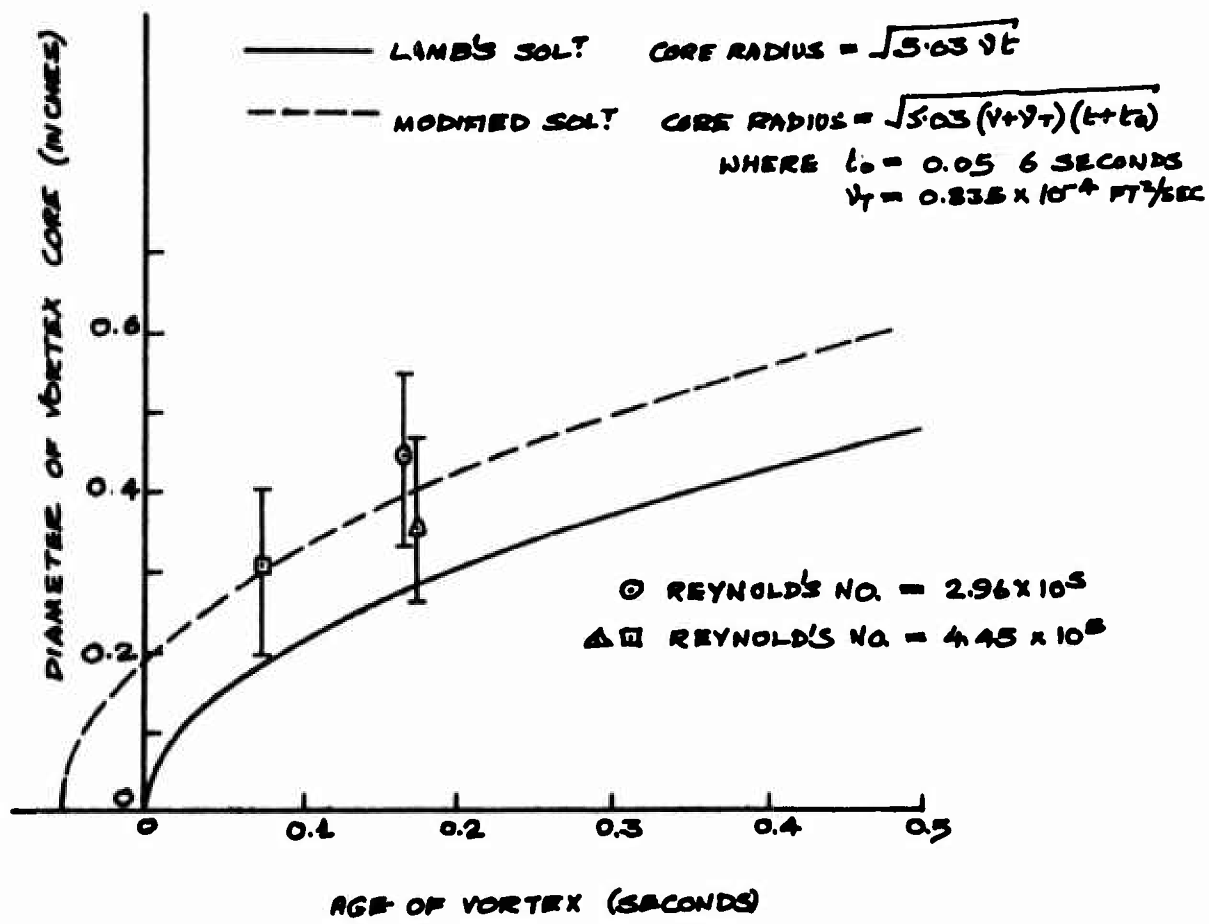

FIG. 7. A comparison of core size with theoretical prediction.

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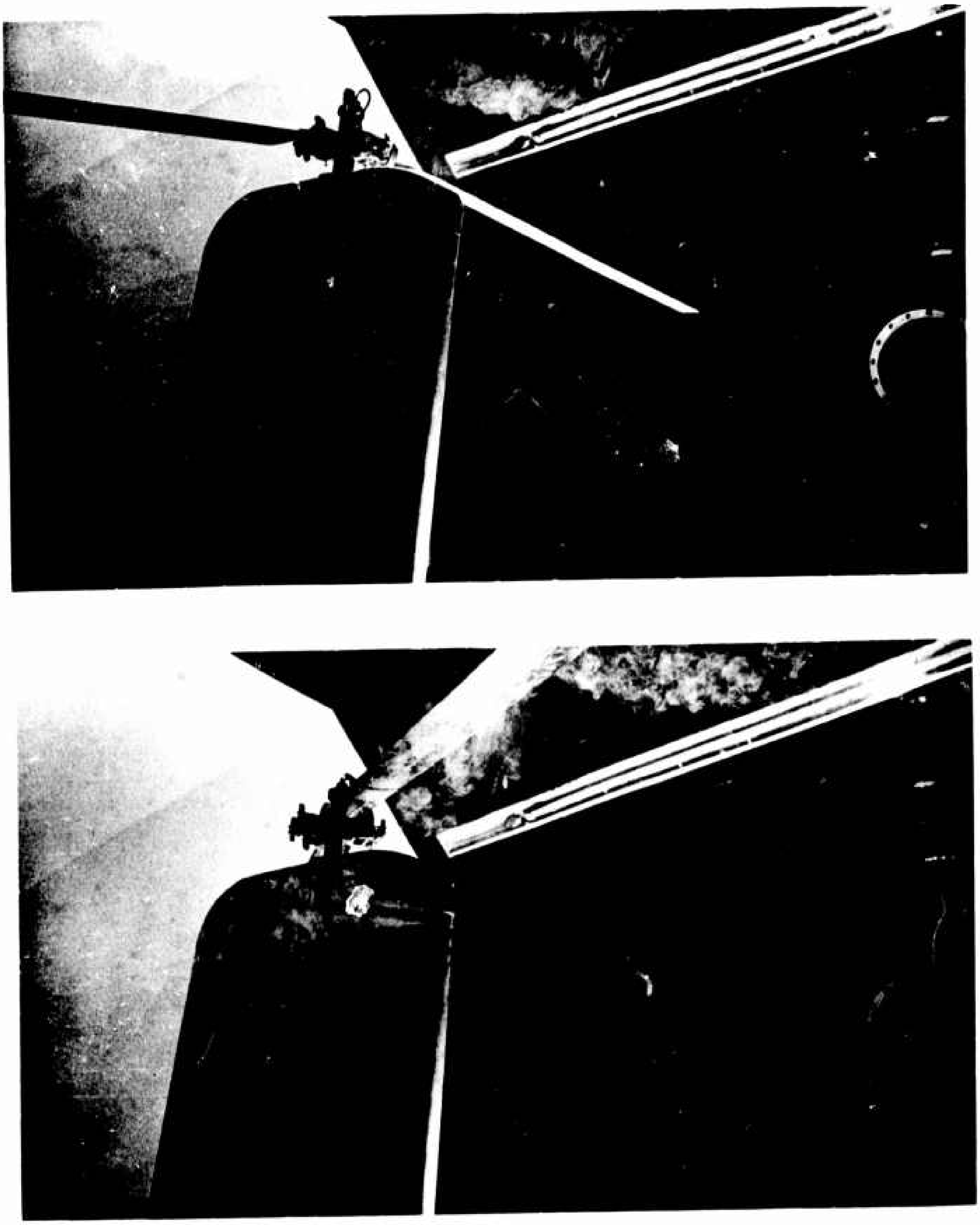

FIG. 8. Movement of Trailing Vortices towards the pylon.
Rotor speed 60 r.p.m. Wind speed 2.75 ft./sec.
Collective pitch 8°. Shaft inclination 8°.

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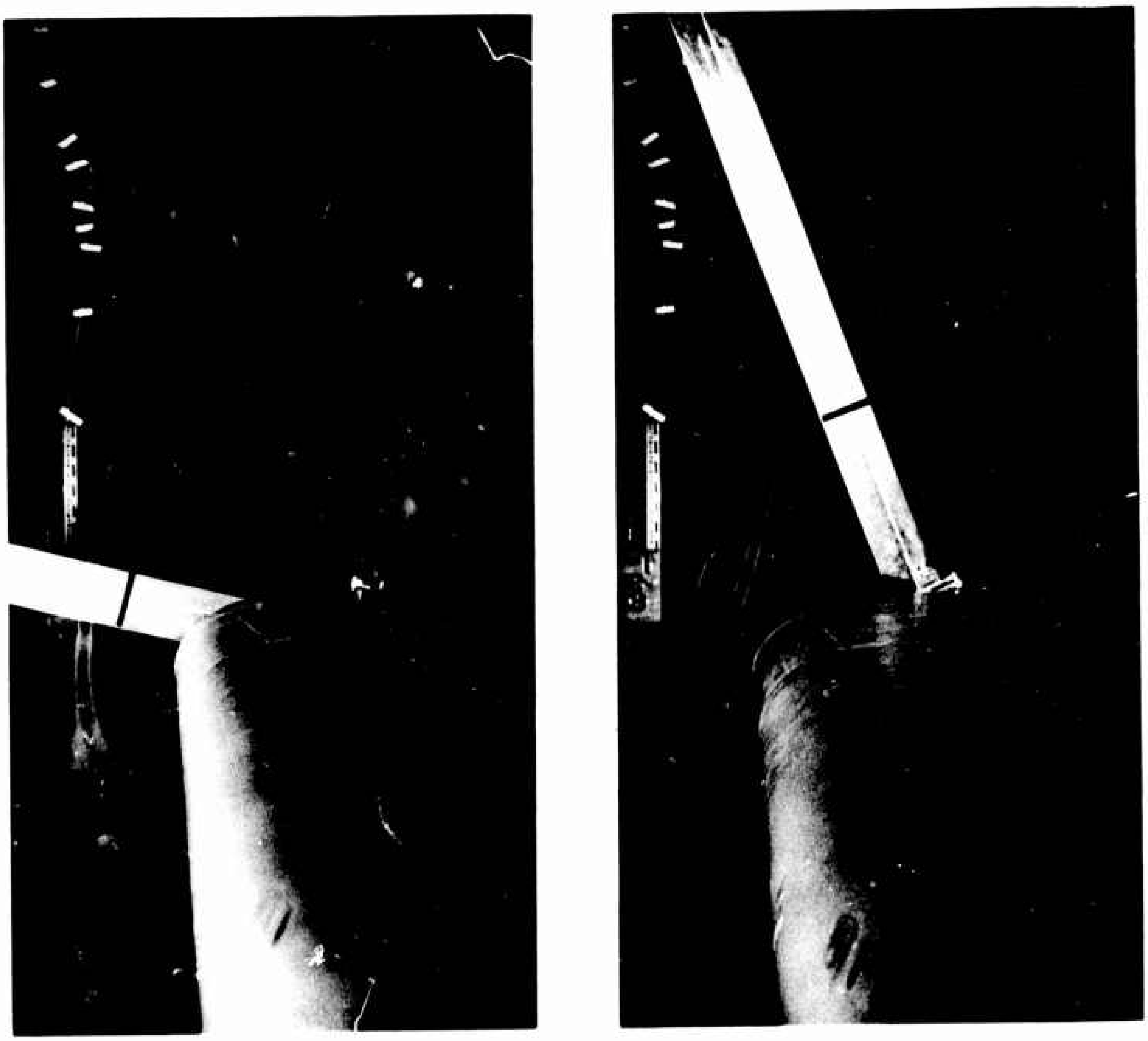

FIG. 9. Vortex/pylon interference. Rotor conditions as for Fig. 8.

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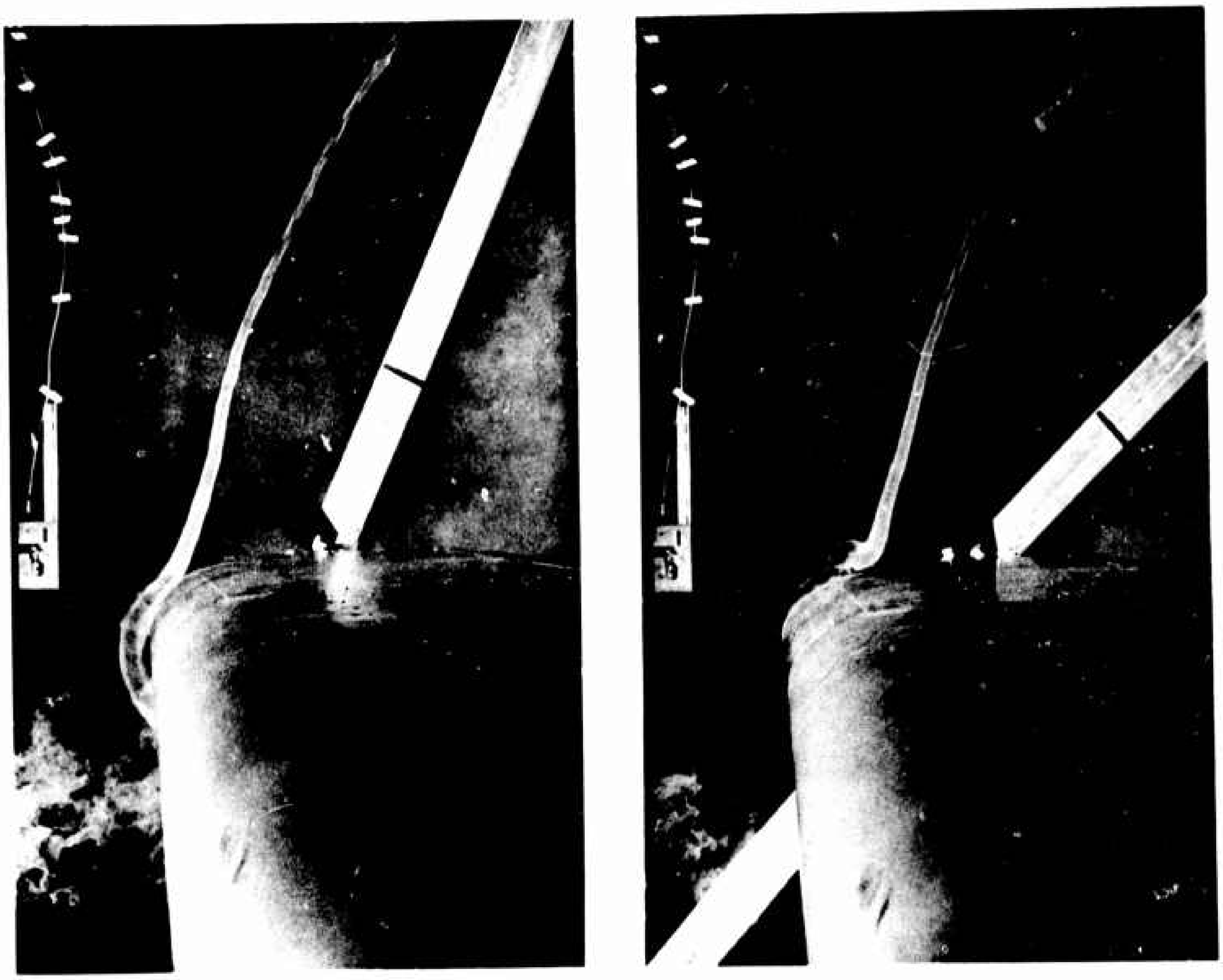

FIG. 9. contd. Vortex/pylon interference.

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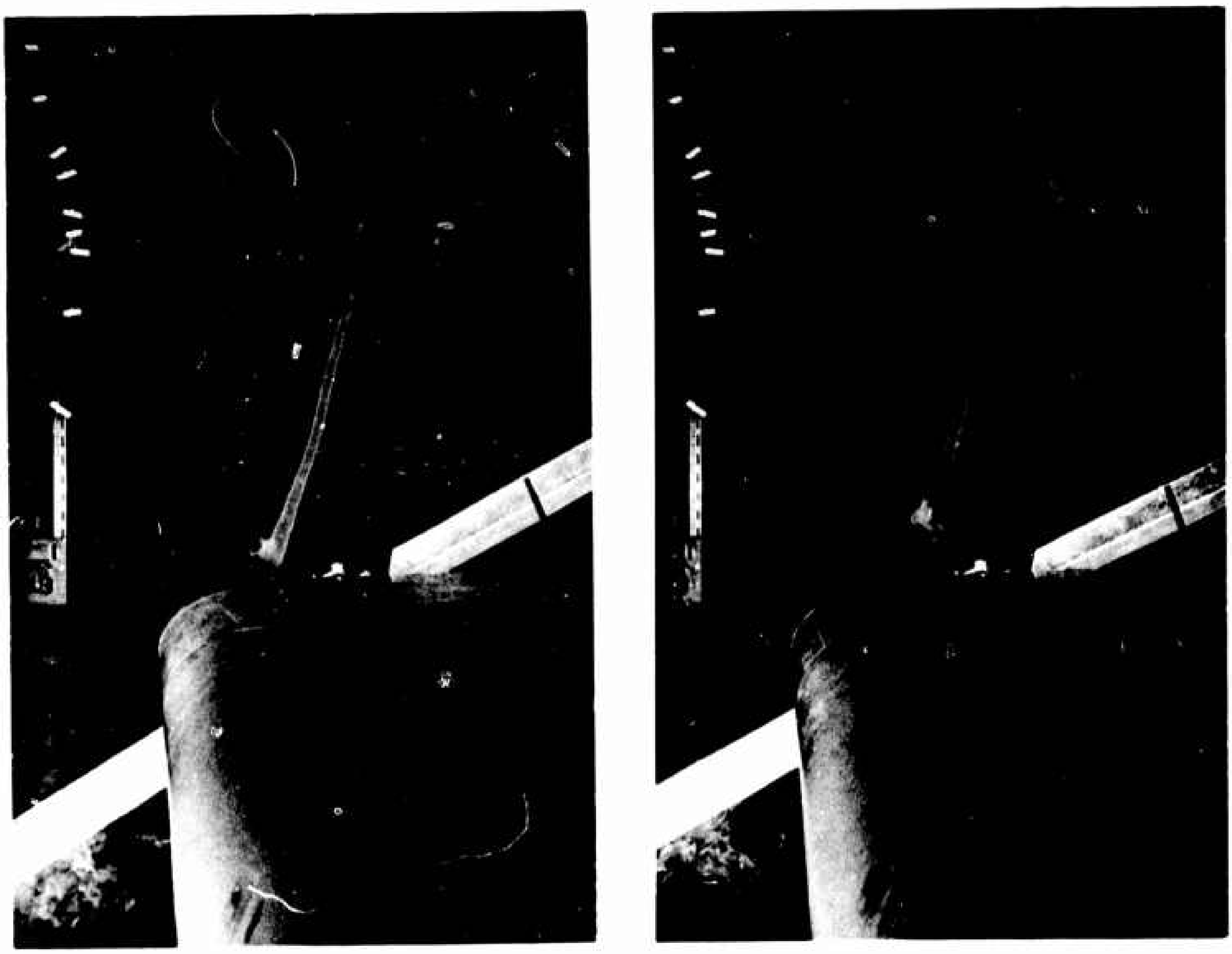

FIG. 9. contd. Vortex/pylon interference.

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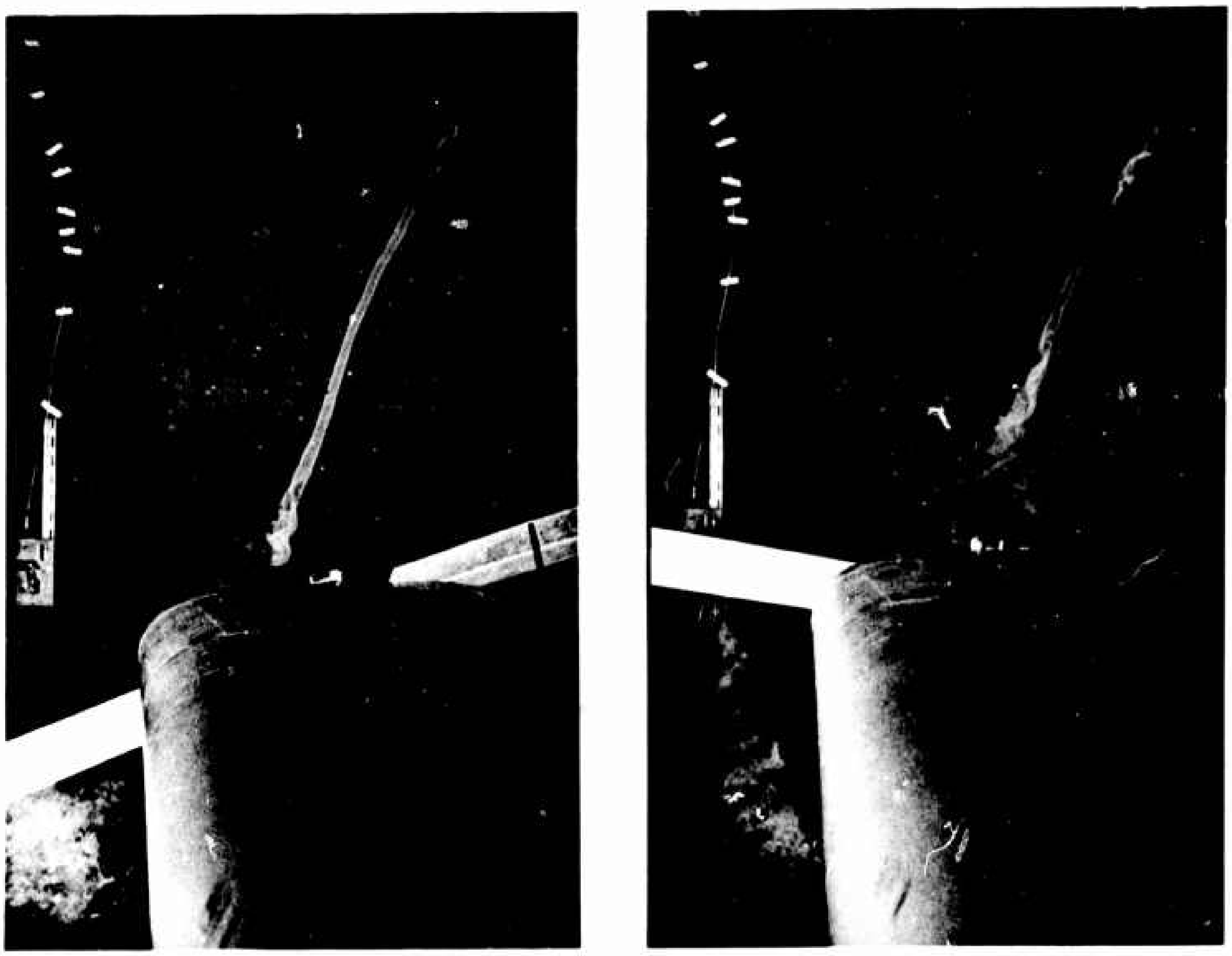

FIG. 9. contd. Vortex/pylon interference.

<u>**28993**</u>

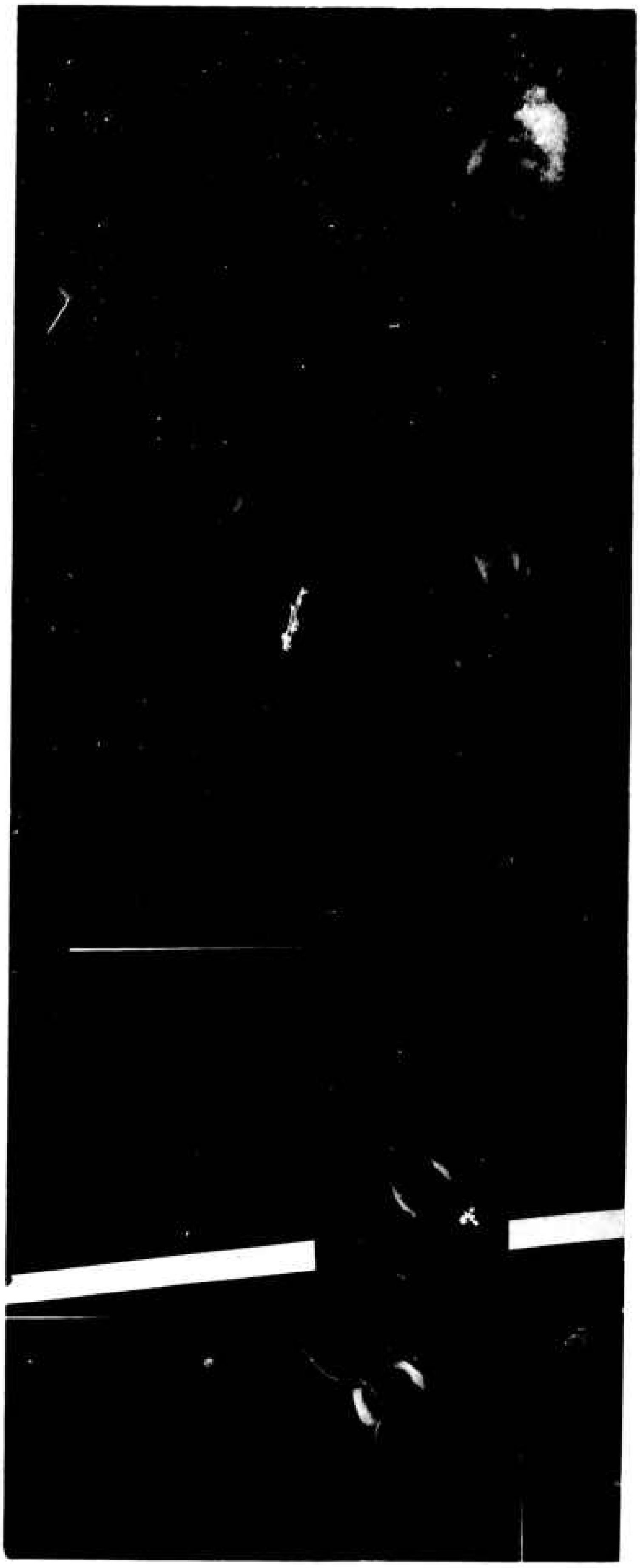

FIG. 10. Cross-section of vortex in vicinity of pylon. Conditions as for Fig. 8.

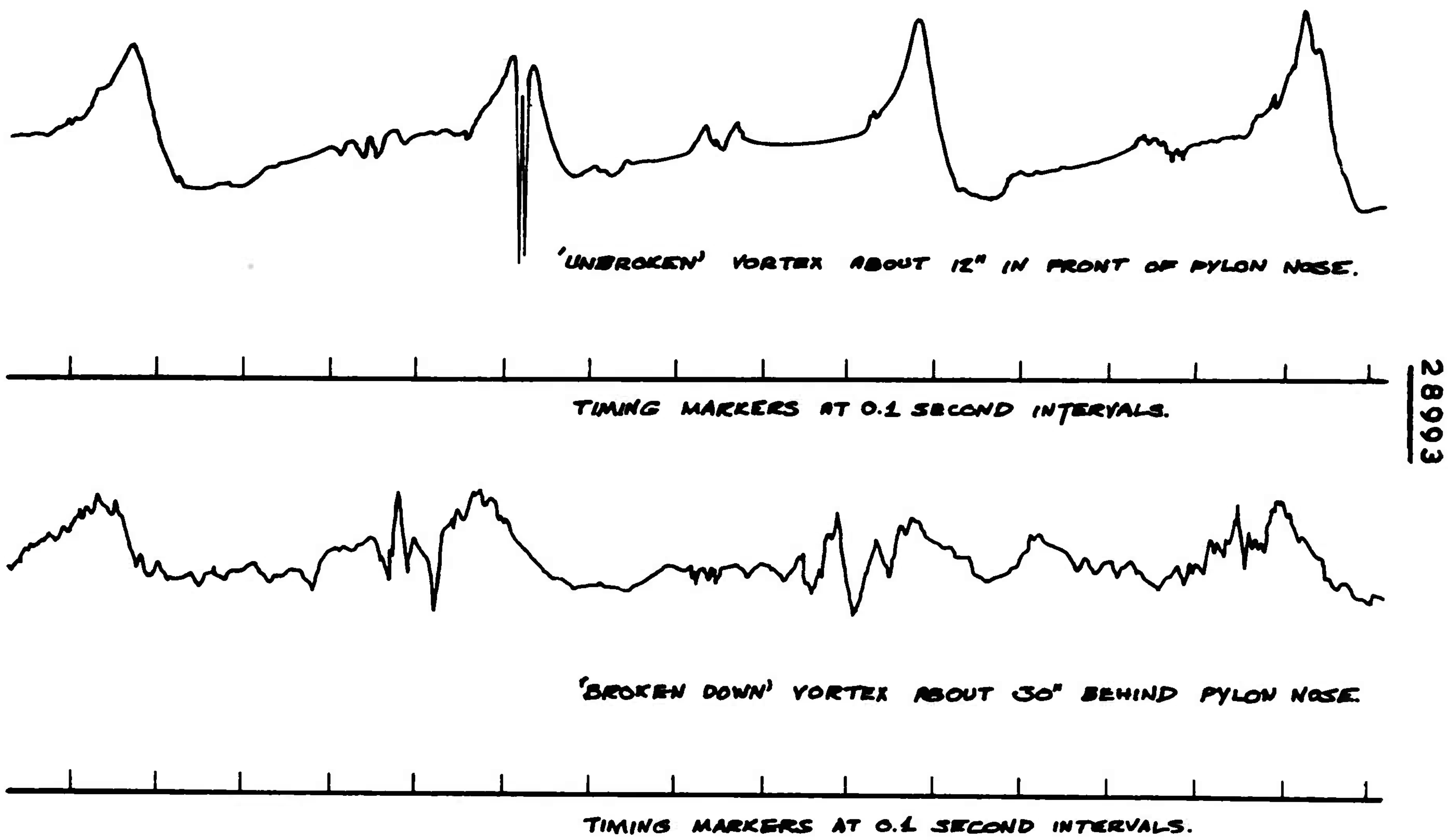

FIG. 11. Hot-wire Anemometer records in the vortex close to the pylon. Conditions as for Fig. 8.

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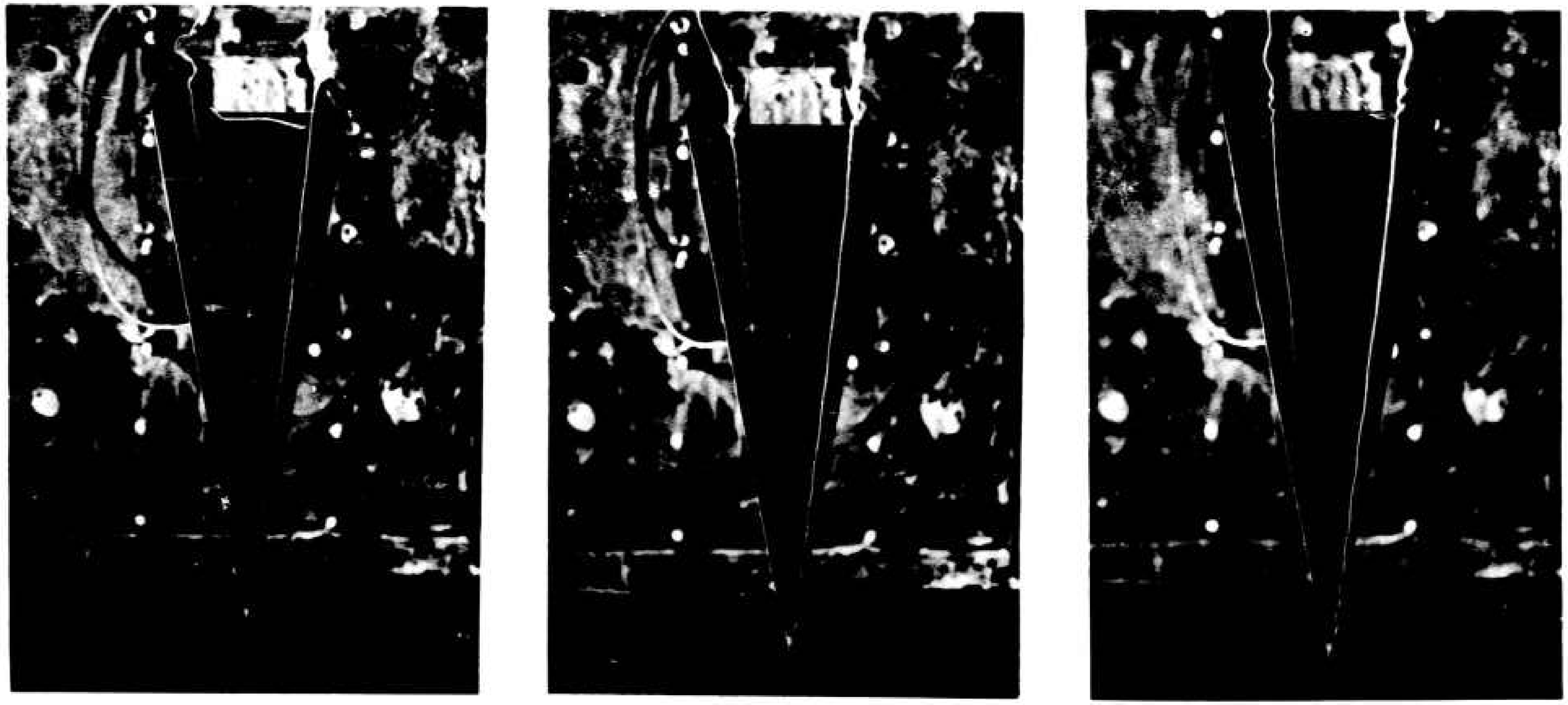

FIG. 12. Development of breakdown in a leading edge vortex.